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C.T. Liu, "Investigating the Effects of Specimen Thickness and Pressure on the Crack Growth Behavior of a Particulate Composite Material"

14th U.S. Congress of Theoretical and Applied Mechanics **(Statement A)**
(Blacksburg, VA, 23-28 June 2002) **(Deadline: 31 Jan 2002)**

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Technical Advisor
Space and Missile Propulsion Division

INVESTIGATING THE EFFECTS OF SPECIMEN THICKNESS AND PRESSURE ON THE CRACK GROWTH BEHAVIOR OF A PARTICULATE COMPOSITE MATERIAL

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1. Abstract

In this study, the effects of specimen thickness and confined pressure on the crack growth behavior in a particulate composite material, containing hard particles embedded in a rubber matrix, were investigated. The experimental data were analyzed and the results are discussed.

2. Introduction

An important engineering problem in structural design is evaluating structural integrity and reliability. It is well known that structural strength may be degraded during its design life due to mechanical or chemical aging, or a combination of these two aging mechanisms. Depending on the structural design, material type, service loading, and environmental condition, the cause and degree of strength degradation due to the different aging mechanisms differs. One of the common causes of strength degradation is the result of crack development in the structure. When cracks occur, the effects of crack sizes and the rate of growth on the fracture resistance of the material need to be investigated.

In recent years, a considerable amount of work has been done studying crack growth behavior in particulate composite materials under different loading conditions at ambient pressure [1-4]. This work was based on linear fracture mechanics. The principles of classical fracture mechanics are well established for single-phase materials. However, experimental evidence indicates that linear fracture mechanics theories have been applied to particulate composite materials with varying degrees of success.

In this study, pre-cracked specimens were used to study crack growth behavior in a particulate composite material, containing hard particles embedded in a rubbery matrix, under a constant strain rate condition at ambient and 8697 Kpa confined pressure. The effects of specimen thickness and pressure on crack growth behavior was investigated and the results are discussed.

3. The Experiments

In this study, single-edge notched tensile specimens made from polybutadiene rubber embedded with hard particles were used in crack propagation tests. The specimens were 1.0 in. wide, 3.0 in. high and the thicknesses of the specimens were 0.2 in., 0.5 in., 1.0 in., and 1.5 in. The geometry of the specimen is shown in Fig. 1.

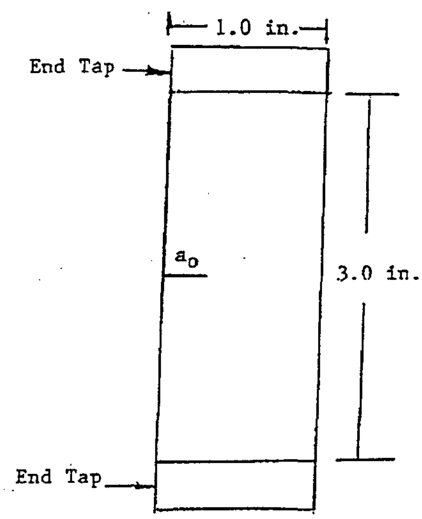

Figure 1 Specimen geometry

Prior to testing, a 0.76 cm. crack was cut at the edge of the specimen with a razor blade. The pre-cracked specimens were tested at an 8 cm/cm/min strain rate under ambient and 8697 Kpa confined pressures. During the tests, a video camera was used to monitor crack growth. The raw data obtained from the tests were the crack length a; the time, t; and the load, p, corresponding to the measured crack length. These raw data were used to calculate the crack growth rate, da/dt, and the Mode I stress intensity factor K_I.

The recorded experimental data, a, t, and p, were used to calculate the Mode I stress intensity factor, K_I, and the crack growth rate, da/dt. In calculating the stress intensity factor, K_I, for a given set of values of a and p, a nonlinear regression equation, which relates the normalized stress intensity factor, K_I/p, to the crack length, a, was used. The values of K_I/p for different crack lengths were determined from the ABAQUS computer program. In calculating the crack growth rate, da/dt, the polynomial method was used. In the polynomial method, a high order polynomial function was selected to fit the crack length versus time data, and the crack growth rate was computed by taking the derivative of crack length with respect to time at a given time. To avoid the time-consuming process of data reduction, a computer program was written to calculate K_I and da/dt.

4. Results and Discussion

It is well known that, on the microscopic scale, a highly filled polymeric material can be considered an inhomogeneous material. When these materials are stretched, the different sizes and distribution of filled particles, the different crosslink density of polymeric chains, and the variation in bond strength between the particles and the binder can produce highly nonhomogeneous local stress and strength fields. Depending on the magnitude of the local stress and the local strength, damage can be developed in the material, especially near the crack tip region. The damage developed in the material may be in the form of microvoids or microcracks in the binder or dewetting between the binder and the filler particles. Damage growth in the material may occur as material tearing or as successive nucleation and coalescence of the microcracks. These damage processes are time dependent and are the main factor responsible for the time sensitivity of strength degradation as well as the fracture behavior of the material.

A typical photograph showing the crack surface during the earlier stage of crack growth under ambient pressure is shown in Fig. 2. Experimental results indicate that crack tip blunting takes place both before and after crack growth. The material at the tip of the crack suffers very large elongation and is nearly straight. The highly strained or damaged zones extend ahead of the crack tip, appearing as an equilateral triangle with the crack tip as its base. This damage zone is known as the failure process zone, which is a key parameter in viscoelastic fracture mechanics [5-6]. When the local strain reaches a critical value, small voids are generated in the failure process zone. Due to the random nature of the microstructure, the first void is not restricted to the surface where the maximum normal strain occurs. Since the tendency of the filler particle to separate from the binder under a triaxial loading condition is high, it is expected that voids, or a damage zone, will also be generated in the specimen's interior. Consequently, there are a large number of strands, essentially made of binder material, which separate the voids that form inside the failure process zone.

As the applied strain increases with time, material fracture occurs at the blunted end of the crack tip. This will always be the location of the maximum local strain. The failure of the material between the void and the crack tip causes the crack to grow into the failure process zone. This kind of crack growth mechanism continues until the main crack tip reaches the front of the failure process zone. When this occurs, the crack tip resharpens temporarily.

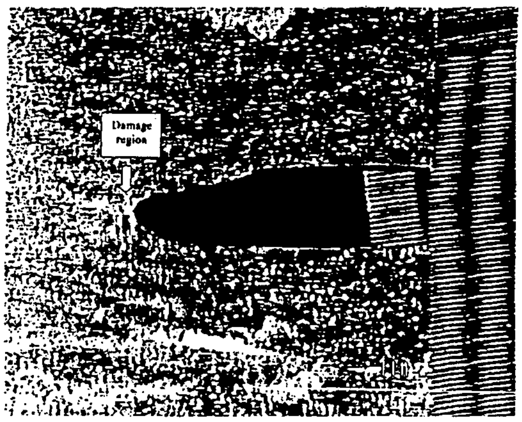

Figure 2 Crack tip profile under ambient pressure

The above paragraphs discuss the damage and crack growth mechanisms when the specimen is strained under ambient pressure. The formation of voids in the material, especially in the highly damaged zone near the crack tip, is a typical damage mechanism observed at ambient pressure. In order to obtain a fundamental understanding of the effect of confined pressure on the crack growth behavior, the effects of pressure on damage initiation and evolution processes need to be investigated. The results of a preliminary study are shown in the following paragraph.

The effects of confined pressure and applied strain on volume dilatation, which is due to the formation of voids in the material, in smooth specimens, are shown in Fig. 3. It is seen that the volume dilatation decreases as the confined pressure is increased. At 8697 Kpa confined pressure, the volume dilatation approaches zero. This phenomenon is mainly due to the suppression of the formation of voids and increase the debond stress at the interface between the filler particles and the matrix. Under this condition, it is conjectured that, instead of the development of voids, micro cracks are developed in the matrix material. The number of micro cracks increases with increasing applied strain, and eventually, a macro crack is formed as a result of the coalescence of the micro cracks. The propagation of the macro crack leads to the fracture of the specimen. Experimental data revealed that for specimens without pre-crack, micro cracks started to develop approximately at 30% applied strain and the number of the micro cracks increased significantly at 40% applied strain (Fig.4) and specimens fractured at 50% applied strain as a result of the fast propagation of a long macro crack.

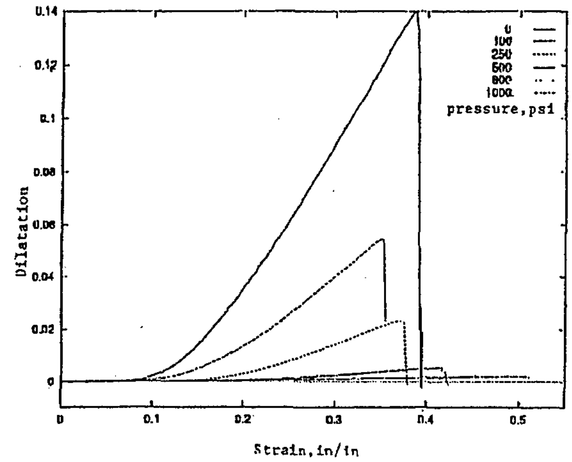

Figure 3 Volume dilatation vs. pressure

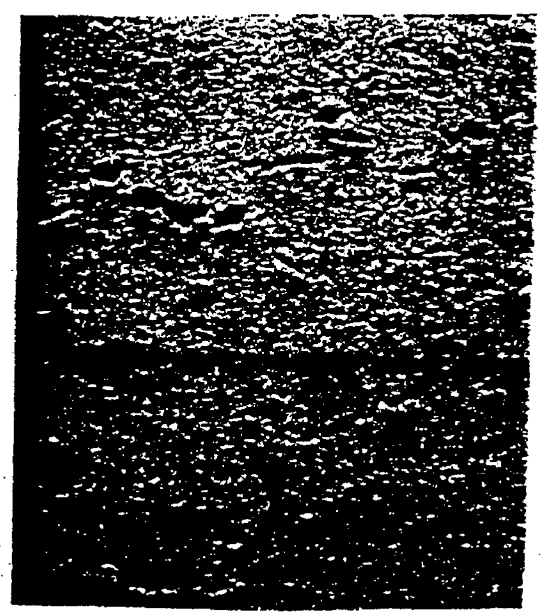

Figure 4 Microcracks in the specimen under pressure

The above paragraph describes the damage mechanisms in smooth specimen under confined pressure. In the following paragraphs, the crack growth behavior in pre-crack specimen under ambient and 8697 Kpa confined pressure is discussed.

Under ambient pressure, experimental data reveal that the crack starts to propagate when the applied stress reaches a critical value, which is in the neighborhood of the maximum stress, as shown in Fig. 5. Once the crack starts to grow, the high crack growth rate results in a fast fracture of the specimen. In other words, unstable crack growth occurs as soon as the crack starts to grow. This type of crack growth behavior is similar to the brittle fracture observed in metals. Therefore, in this study, there is no crack growth analysis conducted under ambient pressure, and only the critical Mode I stress intensity factor, K_{Ii}, for the onset of crack growth is calculated. The results of analysis are shown in Fig. 6. From Fig. 6, it is seen that the variations of K_{Ii} among different specimen thicknesses are within experimental scatter. Therefore, as a first approximation and for engineering applications, it can be assumed that K_{Ii} for the onset of crack growth is independent of specimen thickness. A similar conclusion can be draw for K_{Ii} under 8697 Kpa confined pressure as shown in Fig. 7

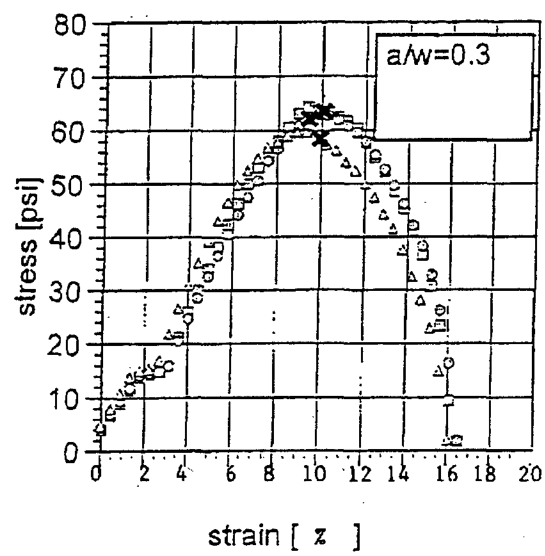

Figure 5 Stress-Strain curve under pressure

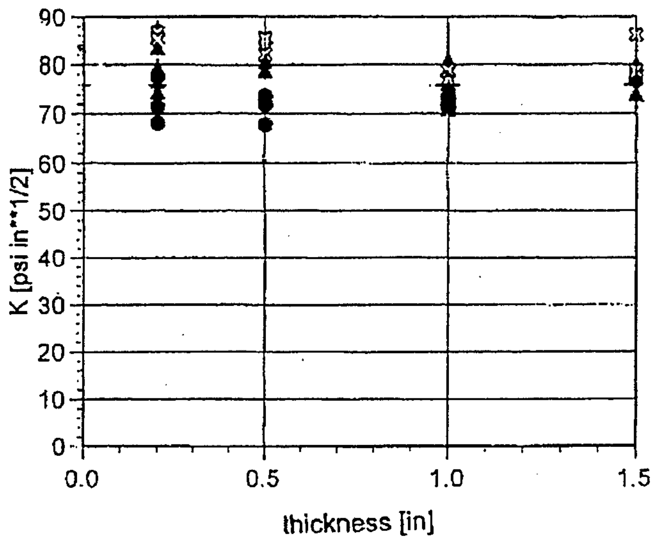

Figure 6 Mode I stress intensity factor vs. specimen thickness. (ambient pressure)

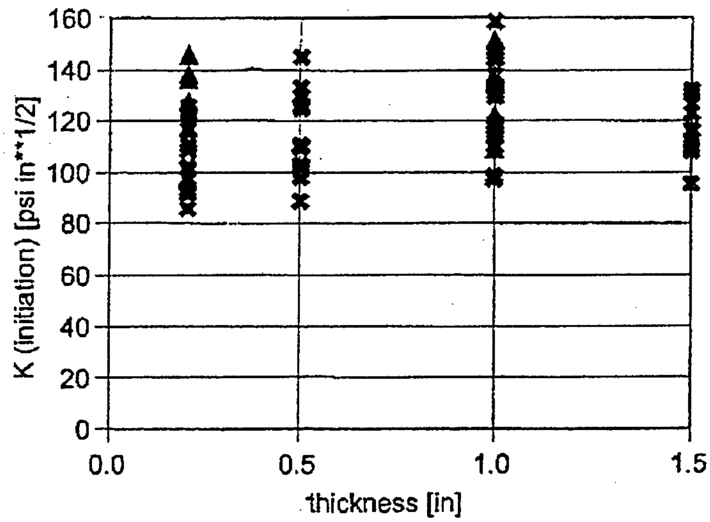

Figure 7 Mode I stress intensity factor vs. specimen thickness. (1000 psi pressure)

It is known that one of the most important practical aspects of linear elastic fracture mechanics for single-phase materials is the concept of the plain strain value of the critical stress intensity factor, K_{IC}. This is because this value (K_{IC}) is perceived to be the minimum critical value and that, for a given material and test environment, it exhibits a constant value to within a certain experimental scatter. This value is usually obtained from a tensile test where the specimen size is adjusted to produce sufficient thickness for the through-the-thickness cracked specimen to induce a brittle fracture. Under this condition, the crack

front will bow in the direction of the crack growth, creating a thumbnail shape. This suggests that there is a plane strain constraint in the center portion of the specimen, which diminishes near the side boundary. However, this may not be true for highly filled polymeric materials. Experimental data obtained from crack propagation tests on highly filled polymeric material specimen revealed that the crack front exhibited no "thumbnailing" both before and after growth. In other words, the crack front was ideally straight, but with local irregularities. The straight crack front observed in solid propellants is believed to be due to the development of a highly damaged zone at the crack tip. The development of the highly damaged zone together with the straight crack front suggests that, within the highly damaged zone, the transverse constraint is very small and that the plane strain fracture toughness does not exist for these materials. The independence of K_{Ii} to the variation of the specimen's thickness indicates that the highly filled particulate composite material behaves differently from metals, and concepts that appeared clear in one instance are only found to contradict physical reality in another.

In order to obtain a fundamental understanding of the effect of damage at a crack tip on the fracture toughness, and also to determine damage initiation and evolution processes near the crack tip, three-dimensional numerical modeling analyses were conducted, based on a micro-macromechanical approach [7]. A detailed description of the numerical model and micro-macromechanical analysis are shown in Reference 7. Therefore, only the relevant results are presented in the following paragraph.

The initiation and evolution of damage at the crack tip near the center and near the surface of the specimen were determined and the results are shown in Fig. 8. It is noted that damage initiated earlier near the center than near the surface of the specimen. Since the damage state is closely related to the stress state, the difference in the damage initiation processes is due to the differences between the stress states near the center and near the surface of the specimens. It is known that near the center of the specimen, the stress state is close to the plane strain stress state as a result of relatively high constraint developed near the center of the specimen. However, near the surface of the specimen, the stress state is close to plane stress conditions. It is known that under a triaxial loading condition, it is relatively easy to develop microcracks in the binder and/or debonds at particle-binder interface. Therefore, it is expected that damage will initiate earlier near the center of the specimen. When the material is damaged, the stiffness, the magnitude of the stress, and the constraint in the damaged region will be reduced. Consequently, redistribution of the stresses occurs and the material adjacent to the damaged material will be subjected to a higher stress that, in turn, will induce damage to the material. These stress redistribution and damage evolution processes continue, and eventually all of the material in the immediate neighborhood of the crack is damaged, i.e., the thickness of the damaged material at the crack tip is equal to the thickness of the specimen. Under this condition, the constraints, both in-plane and out of plane, become insignificant. The uniform distribution of the damage along the crack front will result in a uniform distribution of stress. Since the crack growth behavior is controlled by the local stress at the crack tip, the uniform distribution of stress along the crack front will also result in a relatively straight crack front, as observed experimentally.

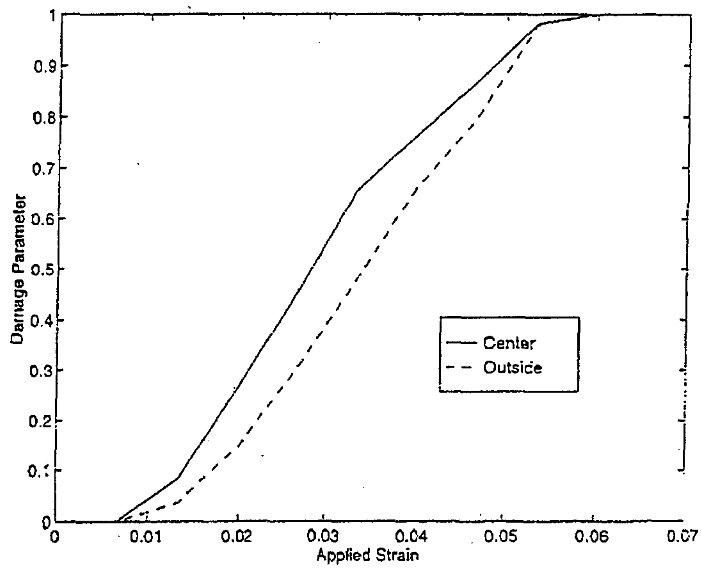

Figure 8 Damage distribution near the center and the surface of the specimen.

Referring back to Fig. 8, it is seen that in the early stage of damage evolution, the damage rate, expressed as the damage parameter per the applied strain, or the slope of the damage parameter versus the applied strain curve, is higher near the center than that near the surface of the specimen. However, the damage rate near the center of the specimen starts to decrease when the applied strain reaches 3% and the opposite is true near the surface of the specimen. Finally, damage saturation occurs near the center and the surface of the specimen at 6% applied strain level, resulting in a uniform distribution of damage at the crack tip and a straight crack front.

In order to investigate the effect of damage at the crack tip on the distribution of K_I along the crack front a three-dimensional linear elastic finite element analysis was conducted by Liu [8]. The results indicate that if there is no damage at the crack tip, the value of K_I at the center of the specimen is about 12% higher than that near the surface of the specimen. However, when through-thickness damage occurs at the crack tip, the distribution of K_I along the crack front is uniform. Since crack growth rate is control by K_I, it is expected that a constant K_I along the crack front will lead to a straight crack front as mentioned before.

A typical plot of the stress–strain curve of pre-crack specimen under 8697 Kpa confined pressure is shown in Fig. 9. It is noted that, unlike ambient pressure test, the crack starts to grow in the linear region of the stress-strain curve and a considerable amount of stable crack growth occurs after the crack propagates. Under this condition, we calculated the crack growth rate, da/dt, and the Mode I stress intensity factor, K_I, and determined the relationship between da/dt and K_I. The results are discussed in the following paragraphs.

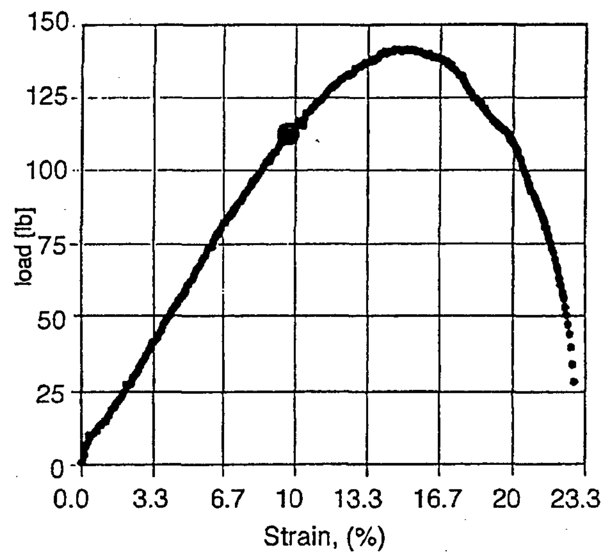

Figure 9 Stress-Strain curve under 1000 psi pressure.

The determination of the crack growth rate requires an analysis of discrete data relating the instantaneous time, t, to the corresponding crack length, a. Due to the nonhomogeneous nature of the particulate composite material, the measured data shows a considerable scatter. Therefore, it is anticipated that a smooth and steadily increasing relationship between the crack growth rate and time is difficult to obtain, and the different methods of da/dt calculation may result in different solutions [9]. Therefore, when selecting a method to calculate the crack growth rate from the raw experimental data, the accuracy and the scatter introduced into the calculated crack growth rate by the selected data reduction method should be considered. As pointed by Liu (9), the secant method introduces a pronounced fluctuation of da/dt whereas the polynomial method results in a continuous smooth crack growth velocity curve. It is important and interesting to note that the fluctuation of da/dt, calculated by the secant method, is consistent with experimental observation. Based on experimental evidence, in general, the crack does not grow in a continuous and smooth manner. During the crack growth process, crack growth rate both accelerates and decelerates. Therefore, the secant method appears to provide the best estimate of both the actual crack growth process and the actual crack growth rate. However, it was found that the crack growth rate calculated by the secant method oscillates approximately around the smooth crack growth rate curve, obtained by the polynomial method. Therefore, if one is interested in knowing the average crack growth behavior, the fluctuation in crack growth rate seems unimportant and the polynomial method can be used to calculate the crack growth rate. Based on this argument the polynomial method was used to calculate the crack growth rate in this study.

A typical plot of crack growth rate da/dt versus the stress intensity factor K_I for initial crack lengths of 0.1 in. and 0.3 in. is shown in Fig. 10. From Fig. 10, a power law

relationship exists between log (da/dt) and log (K_I), which can be mathematically expressed as:

$$da/dt = C_1 K_1^{C2}$$

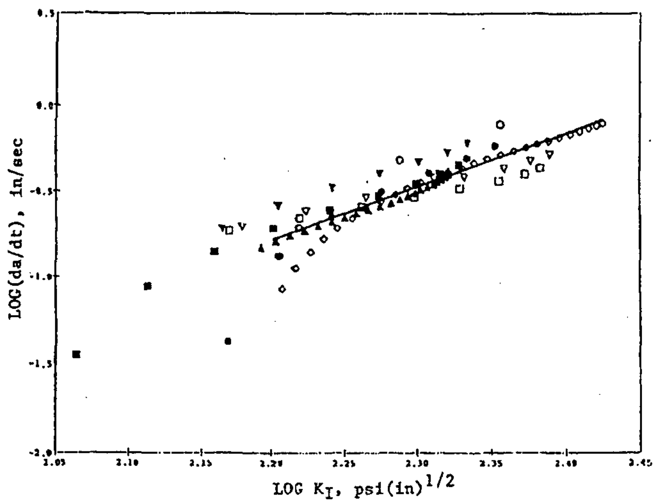

Figure 10 Crack growth rate vs. Mode I stress intensity factor.

5. Conclusions

In this study, the effects of specimen thickness and confined pressure on damage mechanisms and crack growth behavior in a particulate composite material were investigated. Experimental results indicate that, the critical Mode I stress intensity factor, $K_{Ii,}$ for the onset of crack growth is insensitive to the specimen's thickness. Therefore, on the first approximation, it can be assumed that K_{Ii} is independent of the specimen's thickness and plane strain fracture toughness does not exist for this material. Experimental results also indicate that brittle fracture occurs under ambient pressure, whereas a considerable amount of stable crack growth occurs under 8697 Kpa confined pressure. Under the stable growth condition, a power law relationship exists between the crack growth rate and the Mode I stress intensity factor.

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